

Probing Supersymmetry with Neutral Current Scattering Experiments

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Abstract. We compute the supersymmetric contributions to the weak charges of the electron (Q_W^e) and proton (Q_W^p) in the framework of Minimal Supersymmetric Standard Model. We also consider the ratio of neutral current to charged current cross sections, R_ν and $R_{\bar{\nu}}$ at ν ($\bar{\nu}$)-nucleus deep inelastic scattering, and compare the supersymmetric corrections with the deviations of these quantities from the Standard Model predictions implied by the recent NuTeV measurement.

INTRODUCTION

In the Standard Model (SM) of particle physics, the predicted running of $\sin^2 \theta_W$ from Z-pole to low energy: $\sin^2 \theta_W(0) - \sin^2 \theta_W(M_Z) = 0.007$, has never been established experimentally to a high precision. $\sin^2 \theta_W(M_Z)$ can be obtained through the Z-pole precision measurements with very small error. However, no determination of $\sin^2 \theta_W$ at low energy with similar precision is available. More recently, the results of cesium atomic parity-violation (APV) [1] and ν - ($\bar{\nu}$)- nucleus deep inelastic scattering (DIS)[2] have been interpreted as determinations of the scale-dependence of $\sin^2 \theta_W$. The cesium APV result appears to be consistent with the SM prediction for $q^2 \approx 0$, whereas the neutrino DIS measurement implies a $+3\sigma$ deviation at $|q^2| \approx 100 \text{ GeV}^2$. If conventional hadron structure effects are ultimately unable to account for the NuTeV "anomaly", the results of this precision measurement would point to new physics.

In light of this situation, two new measurements involving polarized electron scattering have taken on added interest: parity-violating (PV) Möller (ee) scattering at SLAC[3] and elastic, PV ep scattering at the Jefferson Lab (JLab)[4]. In the absence of new physics, both measurements could be used to determine $\sin^2 \theta_W$ at the same scale: $|q^2| \approx 0.03 \text{ GeV}^2$, with comparable precision in each case: $\delta \sin^2 \theta_W = 0.0007$. Furthermore, the precision needed to probe new physics effects, e.g. supersymmetry (SUSY), is roughly an order of magnitude less stringent, owing to a fortuitous suppression of the SM electron and proton weak charge: $Q_W^p = -Q_W^e = 1 - 4\sin^2 \theta_W \approx 0.1$ at tree-level. Consequently, experimental precision of order a few percent, rather than a few tenths of a percent, is needed to probe new physics corrections.

The goal of our study is to develop consistency check for theories of new physics using the low energy neutral current scattering measurements. In particular, we will consider the Minimal Supersymmetric Extension of SM (MSSM)[5], which is the most promising candidate for new physics beyond SM. For R -parity conserved MSSM, low-energy

precision observables experience SUSY only via loop effects involving virtual supersymmetric particles. Tree level corrections appear once R -parity is broken explicitly. We studies both the PV electron scattering (PVES) and ν ($\bar{\nu}$)-nucleus DIS processes. Details of the calculations presented here can be found in Ref. [6] and [7].

RADIATIVE CONTRIBUTION TO WEAK CHARGE

The weak charge of a particle f is defined as the strength of the effective $A(e) \times V(f)$ interaction: $\mathcal{L}_{EFF}^{ef} = -\frac{G_\mu}{2\sqrt{2}} Q_W^f \bar{e} \gamma_\mu \gamma_5 e \bar{f} \gamma_\mu f$. With higher-order corrections included, the weak charge can be written as $Q_W^f = \rho_{PV} \left[2T_3^f - 4Q_f \kappa_{PV} \sin^2 \theta_W \right] + \lambda_f$. The quantities ρ_{PV} and κ_{PV} are universal, while the correction λ_f , on the other hand, does depend on the fermion species. At tree-level, one has $\rho_{PV} = 1 = \kappa_{PV}$ and $\lambda_f = 0$, while at one-loop order $\rho_{PV} = 1 + \delta\rho_{PV}^{SM} + \delta\rho_{PV}^{SUSY}$, and similar formulae apply to κ_{PV} and λ_f .

The counterterm $\delta\hat{G}_\mu$ determined by muon life time and the Z^0 boson self-energy are combined into ρ_{PV} (expressed in terms of the oblique parameters S, T [8]):

$$\rho_{PV} = 1 + \frac{\delta\hat{G}_\mu}{G_\mu} + \frac{\hat{\Pi}_{ZZ}(0)}{M_Z^2} = 1 - \frac{\hat{\Pi}_{WW}(0)}{M_W^2} + \frac{\hat{\Pi}_{ZZ}(0)}{M_Z^2} - \hat{\delta}_{VB}^\mu = 1 + \hat{\alpha}T - \hat{\delta}_{VB}^\mu. \quad (1)$$

The quantity $\hat{\delta}_{VB}^\mu$ denotes the the electroweak vertex, external leg, and box graph corrections to the muon decay amplitude.

$Z - \gamma$ mixing and parity-violating electron-photon coupling $F_A^e(0)$ contribute to κ_{PV} :

$$\begin{aligned} \kappa_{PV} = & 1 + \frac{\hat{e} \hat{\Pi}_{\gamma Z}(q^2)}{\hat{s} q^2} + 4\hat{e}^2 F_A^e(0) + \frac{\delta\hat{s}_{new}^2}{\hat{s}^2} = 1 + \left(\frac{\hat{e}^2}{\hat{e}^2 - \hat{s}^2} \right) \left(\frac{\hat{\alpha}}{4\hat{s}^2 \hat{e}^2} S - \hat{\alpha}T + \hat{\delta}_{VB}^\mu \right) \\ & + \frac{\hat{e}}{\hat{s}} \left[\frac{\hat{\Pi}_{Z\gamma}(q^2)}{q^2} - \frac{\hat{\Pi}_{Z\gamma}(M_Z^2)}{M_Z^2} \right] + \left(\frac{\hat{e}^2}{\hat{e}^2 - \hat{s}^2} \right) \left[-\frac{\hat{\Pi}_{\gamma\gamma}(M_Z^2)}{M_Z^2} + \frac{\Delta\hat{\alpha}}{\alpha} \right] + 4\hat{e}^2 F_A^e(q^2) \end{aligned} \quad (2)$$

The shift $\delta\hat{s}_{new}^2$ in \hat{s}^2 follows from the definition of \hat{s}^2 in terms of α , G_μ , and M_Z [6].

The non-universal contribution λ_f to the weak charge is determined by the sum of the the renormalized vertex corrections and the box graphs.

SUSY CORRECTION TO WEAK CHARGES

In order to evaluate the potential size of SUSY loop corrections, a set of about 3000 different combinations of SUSY-breaking parameters was generated. Fig. 1(a) shows the shift in the weak charge of the proton, $\delta Q_W^p = 2\delta Q_W^u + \delta Q_W^d$, versus the corresponding shift in the electron's weak charge, δQ_W^e , normalized to the respective SM values. The corrections in the MSSM (with R -parity conserved) can be as large as $\sim 4\%$ (Q_W^p) and $\sim 8\%$ (Q_W^e) – roughly the size of the proposed experimental errors for the two PVES

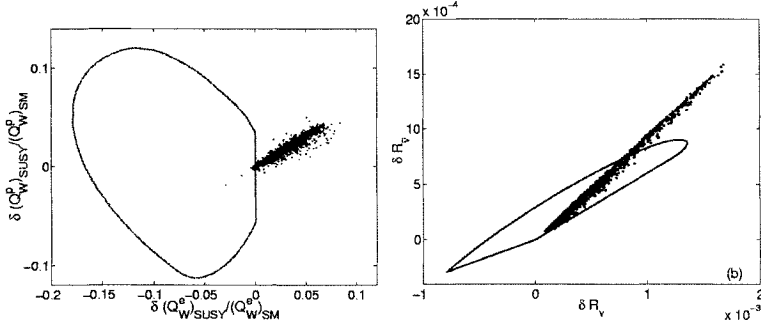


FIGURE 1. Plot(a) shows the relative shifts in electron and proton weak charges due to SUSY effects. Plot(b) shows the MSSM contribution to R_V and R_P . Dots indicate MSSM loop corrections for ~ 3000 randomly-generated SUSY-breaking parameters. Interior of truncated elliptical region gives possible shifts due to RPV SUSY interactions (95% confidence).

measurements. The shifts $\delta Q_W^{e,p}$ are dominated by $\delta \kappa_{PV}^{\text{SUSY}}$, which is nearly always negative, corresponding to a reduction in the value of $\sin^2 \theta_W^{eff}(q^2) = \kappa_{PV}(q^2) \sin^2 \theta_W$ for the PVES experiments. Since this effect is identical for both Q_W^e and Q_W^p , the dominant effect of $\delta \kappa_{PV}$ produces a linear correlation between the two weak charges.

As evident from Fig. 1 (a), the relative sign of the loop corrections to both Q_W^p and Q_W^e is nearly always the same and positive. This correlation is significant, since the effects of other new physics scenarios can display different signatures. For example, for the general class of theories based on E_6 gauge group, with neutral gauge bosons Z' having mass < 1000 GeV, the effects on Q_W^p and Q_W^e also correlate, but $\delta Q_W^{e,p}/Q_W^{e,p}$ can have either sign in this case[9, 10]. In contrast, leptoquark interactions would not lead to discernible effects in Q_W^e but could induce sizable shifts in Q_W^p [9, 10].

As a corollary, we also find that SUSY loop corrections to the weak charge of cesium is suppressed: $\delta Q_W^{Cs}/Q_W^{Cs} < 0.2\%$ and is equally likely to have either sign, which is smaller than the presently quoted uncertainty for the cesium nuclear weak charge of about 0.6% [11]. Therefore, the present agreement of Q_W^{Cs} with the SM prediction does not preclude significant shifts in $Q_W^{e,p}$ arising from SUSY. The situation is rather different, for example, in the E_6 Z' scenario, where sizable shifts in $Q_W^{e,p}$ would also imply observable deviations of Q_W^{Cs} from the SM prediction.

New tree-level SUSY contributions to the weak charges can be generated when the R parity in MSSM is not conserved. The effects of R -parity violating (RPV) contribution can be parametrized by positive, semi-definite, dimensionless quantities $\Delta_{ijk}(\tilde{f})$ and $\Delta'_{ijk}(\tilde{f})$ [12], which are constrained from the existing precision data [12]. The 95% CL region allowed in the $\delta Q_W^p/Q_W^p$ vs. $\delta Q_W^e/Q_W^e$ plane is shown by the closed curve in Fig. 1 (a). We observe that the prospective effects of RPV are quite distinct from SUSY loops. The value of $\delta Q_W^e/Q_W^e$ is never positive in contrast to the situation for SUSY loop effects, whereas $\delta Q_W^p/Q_W^p$ can have either sign.

Thus, a comparison of the two PVES measurements could help determine which extension of the MSSM is to be favored over other new physics scenarios [10].

NUTEV MEASUREMENT

Recently, the NuTeV collaboration has performed a precise determination of the ratio R_ν ($R_{\bar{\nu}}$) of neutral and charged current deep-inelastic ν_μ ($\bar{\nu}_\mu$)-nucleus cross sections[2], which can be expressed in terms of the effective $\nu - q$ hadronic couplings $(g_{L,R}^{\text{eff}})^2$:

$$R_{\nu(\bar{\nu})} = \frac{\sigma(\nu(\bar{\nu})N \rightarrow \nu(\bar{\nu})X)}{\sigma(\nu(\bar{\nu})N \rightarrow l^{(-+)}X)} = (g_L^{\text{eff}})^2 + r^{(-1)}(g_R^{\text{eff}})^2, \quad (3)$$

where $r = \sigma_{\bar{\nu}N}^{\text{CC}}/\sigma_{\nu N}^{\text{CC}}$. Comparing the SM predictions[13] for $(g_{L,R}^{\text{eff}})^2$ with the values obtained by the NuTeV Collaboration yields deviations $\delta R_{\nu(\bar{\nu})} = R_{\nu(\bar{\nu})}^{\text{exp}} - R_{\nu(\bar{\nu})}^{\text{SM}}$, $\delta R_\nu = -0.0029 \pm 0.0015$, $\delta R_{\bar{\nu}} = -0.0015 \pm 0.0026$.

The numerical results for SUSY contributions to R_ν and $R_{\bar{\nu}}$ via the correction to the effective hadronic couplings $(g_{L,R}^{\text{eff}})^2$ are shown in Fig. 1 (b). For detailed analysis, see Ref. [7]. SUSY loop contributions to R_ν and $R_{\bar{\nu}}$ are smaller than the observed deviations. More significantly, the sign of the SUSY loop corrections is nearly always positive, in contrast to the sign of the NuTeV anomaly. Tree-level RPV contributions to R_ν and $R_{\bar{\nu}}$ are by and large positive. While small negative corrections are also possible, they are numerically too small to be interesting.

CONCLUSION

In summary, we have studied the SUSY corrections to the weak charge of the electron and proton, which could be measured at PV ee and ep scattering experiments. The correlation between these two quantities could be used to distinguish various new physics. We also examined the SUSY contributions to the NuTeV measurements and found that it is hard to explain the NuTeV anomaly in the framework of MSSM.

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